Performances Metrics for CyberCars

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ABSTRACT

CyberCars are road vehicles with fully automated driving capabilities. A fleet of such vehicles forms a Cybernetic Transportation System, for passengers or goods, on a network of roads with on-demand and door-to-door capability. This paper presents a framework for the overall evaluation of the performance of different technologies under development during the project. The evaluation plan describes the individual features of the vehicles as well as the features of the infrastructure and the procedures, which should be used to test and evaluate the performances of these features during the CyberCars project.

1. INTRODUCTION

In many urban environments, the usage of the private automobile has led to severe problems with respect of pollution, noise, safety and general degradation of the quality of life. Alternative solutions to the private automobile with the same flexibility now appear with a new concept of mobility: the automobile is part of the public transportation system and is used as a complement to mass transit and non-motorized transportation. CyberCars are road vehicles with fully automated driving capabilities. A fleet of such vehicles forms a Cybernetic Transportation System (CTS), for passengers or goods, on a network of roads with on-demand and door-to-door capability. The fleet of vehicles is under control of a central management system in order to meet particular demands in a particular environment. At the initial stages, CyberCars are designed for short trips at low speed in urban environment or in private grounds[1].

A major barrier to the development of intelligent systems (vehicles) is the lack of metrics and quantifiable measures of performance. There cannot be a science of intelligent systems without standard units of measure. To do science, you must be able to measure what you are doing and measure the results against some metric. This is something the field of AI, robotics, and intelligent systems has largely ignored. Most research results are in the form of demonstrations rather than experiments with data that that is quantitative and referenced against ground truth. There are few benchmarks or standardized tests wherein performance can be compared [2].

To address the issues of testing and evaluation of performance of CTS, INRIA has begun work in a test course, a test procedure, and a set of performance measurement for CTS[3]. This paper presents a framework for the overall evaluation of CTS by a careful analysis of all its various components. This framework can constitute a guide for the manufacturers of such systems, and for the designers and the users (operators and authorities) of CTS because it should point to all the key features which are needed or which can be included in a system. The evaluation plan describes the individual features of the vehicles as well as the features of the infrastructure and the procedures, which should be used to test and evaluate the performances of these features during the CyberCars project. These procedures could form the basis of standard future procedures accepted by the industry.

In this paper, section 2 describes performance for the CTS vehicle, including basic features, control features, human-machine interface, and fleet management. Then, section 3 and 4 present the performance of two key technologies in CTS, navigation and obstacle detection, respectively. Next, section 5 discusses some other performance in CTS, including platooning, remote control, and energy management. Finally, section 6 ends this paper with some concludes.

Figure 1 CyberCars

2. VEHICLE PERFORMANCE

2.1 Basic Features

The vehicles, which constitute CTS, are described in terms of their mechanical dimensions and performances. This description is similar to any vehicle description and should consist of the following elements:

- Overall dimensions: length, width, height, total weight (without load);
- Chassis architecture: material, construction type, etc;
- Body architecture: materials, style, windows, doors, etc;
- Accessibility: door opening, floor height, flat space inside, wheelchair access, etc;
- Load capacity: number of sitting, standing, children, cargo space, max weight, etc;
- Wheels: number, diameters, wheelbase, tread (front/back), ground clearance, etc;
- Steering: type, number of actuators, minimum turning circle, etc;
- Power plant: type, peak power, energy storage, number of drive wheels;
- Brakes: type, number of brakes, parking brake, emergency brake;
- Performances: maximum speed (flat), maximum slope (full load), maximum acceleration, and maximum deceleration.

2.2 Controls Features

The performance of the control should be evaluated essentially in terms of functions provided (and performances of these functions) and in terms of reliability.

It starts with a full description of the control architecture of the vehicle in terms of its three basic functions: power plant, steering, braking. For each of these functions, the control architecture should be described in terms of type of actuators, type of controllers, type of sensors, and type of connection between these components. The entire control architecture should be synthesized in a graphical sketch.

For the reliability, the vehicle manufacturer should be able to provide an MTBF (Mean Time Between Failures) for each of the individual components of the system (including wiring) and the consequences of the failure of any component. The analysis of the individual or composite failure should be done according to the standard analyses in the industry, such as FMECA (Failure Mode effect and Criticality Analysis). It should include the recovery procedures for each type of failure.

2.3 Human-Machine Interface (HMI)

The performances of the HMI are difficult to define in terms of optimization of the operation. We will therefore describe the performance in terms of features, that is whether they are present or not or with what capacity.

Here are the basic features:

- Type of vehicle demand: button, telephone, web, etc;
- Vehicle access control: card, pin code, mobile phone, etc;
- Type of interface inside vehicle: screen, video, voice, etc;
- Selection of destination: screen, buttons, voice, phone, etc;
- Change of selection;
- Additional services inside vehicle: information, web, voice, etc;
- Fare information and collection.

2.4 Fleet Management

Similarly, the performances of the fleet management are also described in terms of features, which are present or not.

Here are the basic features which could be describe the CTS management system (if they are indeed managed automatically by the computer):

- Vehicles parameters, which can be managed;
- Maximum size of the network in terms of arcs and nodes;
- Management of parking locations;
- Management of charging stations;
- Management of cleaning stations;
- Management of service personnel;
- Customer parameters;
- Fare management: fixed, dynamic, etc;
- Type of vehicle allocation on demand: shortest distance, time, energy;
- Vehicle routing algorithm;
- Energy management: minimum level, charging station management, etc;
- Type of demand system: buttons, tel., web, etc;
- Type of communication with vehicles;
- Response time to a request.

3. NAVIGATION PERFORMANCE

The navigation technology is an essential part of CTS. Therefore, it is one of the key components to be evaluated when deciding on a particular system. This section will describe the key features of a navigation system, how their performances are defined and how we intend to measure them.

The first characteristic of the navigation system is the definition of the network where the vehicle is allowed to run. There are several methods to define the available space for the operation of the CTS vehicles:

- The first and most common method is to define a set of paths, which should be followed more or less accurately by the vehicles. We will call this method the *path following method.*
- The second method is to define all the available space for operation by describing a-priori the location of all the edges of the free space. We will call this method *free ranging on a map method*.
- A third method could be to let the vehicle find by itself the space where it is possible to operate by local analysis of its environment. We would call this method the *artificial intelligence method* but it seems unrealistic for near future systems.

3.1 Path Following Method

The path is usually defined by a number of points on a digital map, which is an accurate representation of the real operating world of the CTS. Usually, there are a number of markers in the environment, which are also identified on the digital map. These markers can be magnets, transponders, magnetic wires, optical markers, etc.

The first characteristic of such a system is the description of the technique to define the network and its cost (in Euros per Km of track). The second characteristic is how accurately the vehicle follows its given trajectory. In fact, this may be important in some locations where we have fixed or potential obstacles, and less important in other places. However, the performance metric will be how accurately the vehicle can follow a given trajectory at a given speed (which may be chosen by the designer or set by the vehicle automatically).

In order to perform this test case, the INRIA test course is built as a typical real life situation for urban CTS. Three measurement points will be defined corresponding to a high-speed straight line, a high-speed curve (20m radius) and a tight turning curve (minimum turning radius of the vehicle).

In order to measure the performance, especially the accuracy, of different navigation system, INRIA has developed a technique to accurately localize CyberCars by both vehicle odometry and landmark localization. We use reflective poles spaced out about 50 m apart and located at the front of the vehicle. The LADAR detects distances, angles, speed, and the position of obstacles within 10 m. Odometry is performed by a steering sensor and an encoder attached at the vehicle differential. Using this information, the embedded system matches the vehicle's computed position with the location of the poles to obtain an accurate vehicle position[4].

In this test, the CTS vehicles will travel at the nominal operational speed, and go through these measurement points with different loads: with the vehicle empty, with ½ maximum load and with maximum load. For each case, the test will be performed 3 times. For each experiment, we will measure the lateral error with respect to the trajectory, as defined a-priory. The performance will be given by the value of the maximum error for all the measures at each point and the speed at which the vehicle was running. It consists therefore of three error values and three speeds, one for each type of operation (high speed straight line, high speed curve, low speed tight curve).

3.2 Free Ranging on Map

In this test case, the operational environment of the vehicles is not defined by a set of trajectories but by the space available for operation. The correspondence between the digital map and the real world may also be done through a set of physical markers.

The first characteristic of this method is the cost of the definition of the digital map and its correspondence with the real world. However, since in this method, there is no exact length of tracks, the cost has to be evaluated with respect to an equivalent number of kilometers of tracks. In general, this is not difficult to evaluate except in very few situations where there is no road to follow. In these situations, the cost will have to be estimated with respect to the total surface of “free space” available for the CTS, that is in terms of Euros per square meter. In all other cases where the vehicles must follow a set of roads, the cost should be evaluated in terms of Euros per kilometer. The precision of the free ranging method is more difficult to evaluate since there is no precise predefined path to follow. The performance will therefore be evaluated with respect to the capacity to go through “gates”.

In order to perform this test, we will define artificial obstacles in the form of gates through which the vehicle must pass at these points. These gates will be defined as small as possible to allow the vehicle to pass at the operational speed.

In this test, the CTS vehicles will travel at the nominal operational speed, in the same three different conditions (high speed straight line, high speed curve, low speed tight curve). As in the previous case, we will define three measurement points. The measurement of the precision will be the measurement of the maximum offset to the center of the gate with respect to the gate width and the speed.

As before, three sets of measurements will be done with three loads for each set.

3.3 Comfort Performances

The goal of the navigation system is to allow the vehicle to go from one location to another location while staying on the defined paths and while maintaining a set of given performances in terms of speed, accelerations and jerks. Of course, there is a tradeoff between speed and comfort (expressed in terms of accelerations and jerks). The performances will be the set of maximum accelerations and jerks (lateral and longitudinal) at various operational speeds.

These performances can be evaluated in ideal situations (straight line, large curve and sharp curve of constant radius) including start and stop, or in real life situations. To simplify the evaluation procedure, we decided to perform this test on the INRIA test course, which is a typical real life situation for urban CTS.

In this test, the designer will optimize the speed profiles (when possible) to attain various average operational speeds on the track with three loads (empty, half and full). The values of acceleration and jerk will be recorded from a high precision IMU (Inertial Measurement Unit), which has been developed at INRIA and will be installed securely (but on a vibration absorbing material) inside the vehicle, if possible on the floor.

3.4 Frequency of Failure

The last performance for the navigation system is its frequency of failure, where the vehicle stops because of the navigation system and must be restarted manually, or worse, veers off the course.

This test should be done by the evaluation team on the INRIA test course in terms of number of failure per 1,000 hours, or its inverse, the MTBF. Since it may be difficult to perform this test over a significant amount of time (several thousands of hours), it should be replaced by actual data collected securely (without any tempering possibility) on any test course.

4. OBSTACLE DETECTION PERFORMANCE

Obstacle avoidance is the key and most crucial element of CTS, which will work in environments, which are not totally protected from intrusion. This is particularly the case when the vehicle will operate among possible pedestrian, cyclist, and possible unforeseen obstacles.

There are numerous technologies, which may be used to implement an obstacle detection coupled with an efficient emergency stop or an avoidance maneuver. We can mention laser beams, millimeter wave radars, ultra-sound sensors, vision systems, etc.

There also numerous obstacles which must be avoided by the vehicle: fixed of moving, on/above/under the ground and these obstacles can be anywhere on the future path of the vehicle. On the other hand, the vehicle should not stop for false obstacles such as an obstacle close to the trajectory but not on it, and objects such as falling leaves, rain or snow.

We will therefore distinguish four kinds of obstacles to avoid and a special procedure to test for false obstacles.

4.1 Fixed Obstacle on the Ground

The CTS vehicle has to decelerate and stop before an obstacle. The following test case represents situations where an obstacle is standing on the trajectory. The system performance is assessed regarding the obstacle detection, the deceleration maneuver, the comfort (jerk during the deceleration) and the distance to the obstacle. A subjective evaluation of the safety feeling may be included.

The major obstacle to be avoided is a human being. In order to test this kind of obstacle, we will perform the test with a fixed dummy obstacle -- a hollow cylinder with a diameter of 15 cm and a height of 50 cm on the ground. The cylinder will be made of plastic or cardboard, at least 3 mm thick and painted flat black.

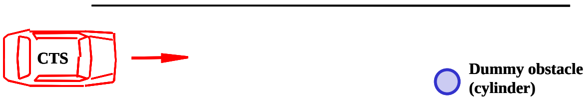

Figure 2 Test with fixed obstacle

In this test, the CTS vehicle travels at the maximum operational speed. The cylinder will be placed on the trajectory of the vehicle horizontally or vertically, either in the center of the path or on each side with 20 cm clearance between the vehicle and the object. For each obstacle position, the test will be performed 3 times. The vehicle should stop in each case. The tests will be performed in straight line, in a large circle (20m radius) and in tight circle (minimum turning radius). The maximum deceleration and maximum jerk will be recorded for each stop. The maximum value for all the positions of the obstacles and for the three tests will be kept. If the test fails once, it is considered that it did not pass.

4.2 Fixed Obstacle above the Ground

This test case is almost same as the previous case, except that the obstacle in the path will not be on the ground, but above the ground, for example, suspended from above or cantilevered from the side. The CTS vehicle should decelerate and stop before this kind of obstacles. The system performance is completely same as that in the previous case.

In order to perform this test case, a gantry at least 2 m away from the vehicle (sideways and above), is used to hold the same dummy obstacle as before. In this test, the CTS vehicle travels at the maximum operational speed. The dummy obstacle will be placed on the trajectory of the vehicle in the same horizontal position and at various heights up to 10 cm above the vehicle. For each obstacle position, the test will be performed 3 times. The vehicle should stop in each case. The tests will be performed in straight line, in a large circle (20m radius) and in tight circle (minimum turning radius). The data should be recorded in the same fashion as before for the obstacle on the ground.

4.3 Negative obstacle

A negative obstacle is a hole or a dip on the surface of the road, which could damage the vehicle and/or its occupants. These obstacles are extremely difficult to detect and it is often ignored with the assumption that the track of the vehicle is known, and should never encounter such accident. However, we should provide the information whether this feature is present or not in the CTS vehicle. The system performance is similar to that in previous test cases.

In order to perform this test, a step is used with a height of 20 cm and a width of 50 cm. In this test, the CTS vehicle travels at the maximum operational speed in straight line. The test will be performed 3 times. The vehicle should stop in front of the step. The data should be recorded in the same fashion as before.

4.4 Moving Obstacle

Moving obstacle avoidance is the most difficult feature of a CTS vehicle. The following test case represents situation where an obstacle, typically a pedestrian or a cycle, is entering the path where a CTS vehicle is traveling. The scenario involves therefore the same safety features as in the previous cases, with the additional difficulty that the obstacle is suddenly entering the area of interest, and the CTS vehicle should react in a short time. The system performance is assessed similarly to the previous cases.

In order to test this function, we will use a moving base holding the previous “dummy obstacle” and able to displace it at a constant speed of 2 m/s. The base should not be higher than 10 cm and should be enclosed in a black cylinder made of plastic or cardboard with a flat top where the “dummy obstacle” is mounted.

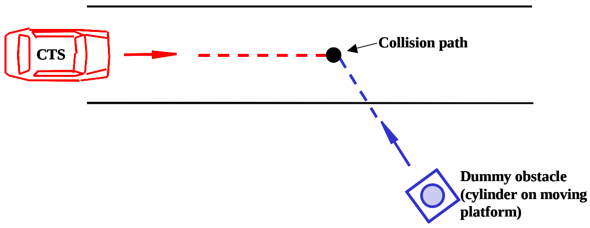

Figure 3 Test with moving obstacle

In this test, the CTS vehicle travels at the maximum operational speed. The dummy obstacle, which is mounted on the moving platform, will cross the path of the CTS vehicle on a collision course by programming in advance or manually operating, so that it would impact the front or side part of the CTS vehicle in case of no reaction or wrong reaction. The angle to the trajectory of the CTS vehicle is assumed 120º. Arrivals from both the right and left side are considered. Each case will be performed three times. The vehicle should react correctly to avoid the potential collision. Unless the test fails once (with a collision), the maximum values of the deceleration and the jerk will be recorded. We will also record the time for the vehicle to resume its operation once the obstacle has cleared the path. Once again, we should try to perform the test in various operating conditions.

4.5 False Obstacles

The CTS vehicle should be able to stop safely in case of a potential obstacle. On the other hand, it is important that the vehicle should not stop in the case there is no danger. However, the obstacle detection systems could be fooled in various situations. We can think of the following, which should be tested in the evaluation of a system:

- **Fixed Obstacle Clearance**

We have seen that the vehicle should stop in case an obstacle lies within 20 cm of its path in all directions (ground, side, above). Now, it should pass with a minimum distance above 20 cm. The performance will be the value of this minimum distance, which allows the vehicle to operate without slowing down.

To simplify the test, we will perform the test only on ground vertical obstacles with the dummy obstacle (cylinder) used in the previous cases. In this test, the CTS vehicle travels at the maximum operational speed. The cylinder will be placed at various positions (>20cm) out of the trajectory of the vehicle. The vehicle should not stop in each case. For each of the three types of tracks (straight, large curve, minimum curve), we will therefore record the minimum distance of a vertical ground obstacle to the track which allows the vehicle to pass without any slowdown, and the minimum distance which allows the vehicle to pass after slowing down but without stopping.

- **Moving Obstacle Clearance**

The false obstacle can also be moving obstacle. Ideally, the vehicle should not change its speed if the clearance is big enough. The system performance will be the slowing down of the vehicle measured in speed, maximum deceleration and jerk if a deceleration occurs.

In order to perform this test case, we will make use of the dummy obstacle and the moving base as used in the previous cases. In this test, the CTS vehicle travels at the maximum operational speed. The dummy obstacle (vertical cylinder) will again be mounted on the moving base operating at 2m/s on a path perpendicular to the trajectory. The moving base should move across the path so that it will clear the vehicle at a distance of approximately 10 meters when it is running at its nominal speed. The test will be performed three times at the maximum nominal speed of the vehicle. One more set of experiments will be performed with distance of 5 meters. Ideally, the vehicle should not change its speed. If the vehicle stops, the performance indicator will be the time to resume its course.

- **Ghost Obstacle**

A ghost obstacle is anything which can be perceived as an obstacle by the obstacle detection system but which would not constitute a significant obstacle for the vehicle. It could be for example a cloud of dust, falling leaves, heavy rain, snow, fog, etc. The performance measurements will be as above: the speed, the deceleration and the jerk if a deceleration occurs.

The test we propose will consist of confetti dropped in front of the vehicle. In this test, the CTS vehicle travels at the maximum operational speed. A 1kg bag of confetti will be released one meter above the vehicle, when it is at 20 meters and at 10 meters. Ideally, the vehicle should not change its speed. If the vehicle stops, the performance indicator will be the time to resume its course.

- **Change of Slope**

In the case of a sudden increase of the slope of the track, the vehicle may see it as an obstacle. We will test the capability of the vehicle to detect this as a correct feature of the track. The performance indicator will be the maximum deceleration and maximum jerk if a slow down occurs.

The configuration will be a course where a change of slope or 10% will occur smoothly over a distance of 5 meters. In this test, the CTS vehicle travels at the maximum operational speed on a straight course. The data should be recorded in the same fashion as before. Ideally, the vehicle should not change its speed. If the vehicle stops, the performance indicator will be the time to resume its course.

5. OTHER PERFORMANCE

5.1 Platooning

The evaluation of the platooning functionality is focused on performance parameters, such as the maximum speed of the convoy, which maintains a safe and stable operation, and the number of vehicles, which can travel on the track in a given time. These quantities are linked to the expected use of platooning, in given application sites, for the relocation of vehicles, or increasing the throughput in terms of vehicles per hours per track (or minimum headway between two vehicles).

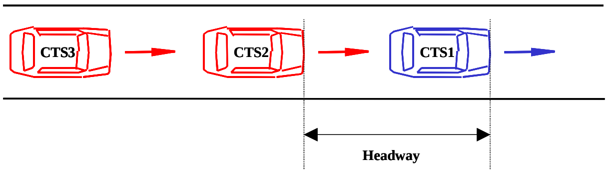

Figure 4 Test with platooning

In this test case, the first vehicle CTS1 is driven manually (or automatically) in a path with straight parts and curves. A second equipped vehicle CTS2 is following the previous leader vehicle, connected by an electronic link, via the distance measuring sensors, or other suitable communication devices. The leading vehicle is driven at different speeds and the following vehicle should maintain the link (ideally at constant distance and the same speed). The scenario includes a braking maneuver (emergency stop) operated by the driver (or the CTS system), to verify that the followers can stop without any collision. The evaluation of platooning performance should be done in various environmental conditions and with various loads in the vehicle. Due to the need to set-up basic performance, the evaluation of string stability is outside the purpose of the present tests. More than one following vehicle can be tested.

5.2 Remote Control

It is important in CTS that a central operator can intervene on the vehicle in case of any incident. This remote control should start by knowing the state of any vehicle at any time, including location, speed, occupation, state of charge, state of all subsystems, etc. However, a central operator should also have a number of actions available to him in order to have a better control over the management of the fleet, in particular in case of disfunctions. These functions could include:

- Emergency remote stop
- Remote control of doors
- Remote restart of the vehicle (e.g. after emergency stop)
- Bi-directional communication (audio and/or video) with passengers
- Speed control
- Direction control

These two last features imply a remote operation of the vehicle and could prove very valuable if a vehicle is stranded because of an obstacle (real or false). In these situations, a remote control capability could allow the central operator to solve the problem without sending an employee to the vehicle.

The performance of the remote operation can be evaluated in terms of the speed which can be obtained safely through various situations and in particular through tight obstacles.

In order to test this feature, INRIA will define a test circuit with poles through which the vehicle must pass. The performances will the capability and the time to go through the circuit in forward and backward (if possible) direction.

5.3 Energy Management

Energy and environment are not the most important issues of the CyberCars Project, which is technology-oriented, and whose main concern is to provide a better transportation system in terms of mobility. However, since the CTS is an environmental friendly system, its energy and environmental aspects must also be evaluated. This is within an overall assessment of the system, including an economic evaluation, which will be performed in the CyberMove Project.

In the CyberCars project, the energy evaluation is focused on the energy technology, and its methodology is based on the following steps:

- Definition of a typical CyberCars driving cycle or several cycles (different scenarios)
- Measurements of energy consumption of CyberCars at available sites
- Simulations, using a simulation model developed as part of the project
- Comparison of energy consumption with conventional cars
- Measurements and simulations of energy transfer during battery charging
- Calculations / estimates of total energy consumption of a CTS, under various scenarios

Note: the data will be presented in energy units, e.g. kWh, and in kWh per person – km, etc.

It is quite difficult to estimate the accuracy and the confidence limits of the energy evaluation. The energy measurements are known to be accurate (within, say, 3%), and the simulation by itself also (same order of accuracy). The other input data, like the vehicle behavior, number of passenger, system operation during different times, etc., is not yet available.

It is noted that the results from this evaluation will serve to perform the energy and environment assessment in the CyberMove Project, which will include calculations and estimates of the whole energy chain – 'well to wheel', and the associated emissions of pollutants and greenhouse gases. All these will be compared with other (conventional) transportation systems. Moreover – the comparisons will be carried out for city centers, where the CyberCars (zero emission vehicles if electric) would run, as well as for the global energy chain, including power plants with fossil fuels, nuclear energy and renewable.

It is noted that the tasks above are not easy to perform at the current stage of CTS development, due to lack of data. Therefore, some of the calculations will depend, initially, on preliminary assumptions. However, it is emphasized that what we are developing here is the evaluation and assessment tools. The results will certainly improve as more data of running systems will be gathered and more information will be accumulated. In this respect, the following issues have to be addressed:

- Typical CyberCars (high degree of uncertainty) results of technologies evaluation are needed, from the other parts of this project task.
- CyberCars driving cycle (based on measurements of vehicles in available CC systems).
- Measurements of CyberCars parameters (which affect the driving behavior) at few available sites as basis for driving cycle development and further simulations (no data is yet available).
- Simulations – energy consumption, dynamic parameters, driving range, etc., will be evaluated for few typical scenarios

6. CONCLUSIONS

This paper presents a framework for the overall evaluation of CTS by a careful analysis of all its various components. This framework can constitute a guide for the manufacturers of such systems, and for the designers and the users of CTS.

The evaluation plan describes the individual features of the vehicles as well as the features of the infrastructure and the procedures, which should be used to test and evaluate the performances of these features during the CyberCars project.

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